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The effects of hypoxia on reaction time and movement time components of a perceptual–motor task

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It has previously been demonstrated that hypoxia disrupts performance on a visual SCRT (serial choice response time) task. Two experiments were conducted to examine further the nature of this disruption. Hypoxia was induced with low-oxygen mixtures and SaO_2 (arterial oxyhaemoglobin saturation) was held at a level equivalent to an altitude of approximately 4700 m. In experiment 1, choice reaction time was measured with a version of the SCRT task that eliminated movement time. Hypoxia increased the intercept but not the slope of the Hick–Hyman function. In experiment 2, movement time was measured with a reciprocal tapping task. Hypoxia increased not only the slope of Fitts' function but also the slopes produced when target width and movement amplitude were analysed separately. In both experiments the error rate was held constant. These results indicate that hypoxia disrupts the reaction time and movement time components of SCRT performance. It is proposed that reaction time is slowed rather than 'blocked' and that decreased brightness sensitivity contributes to this slowing but the choice processing stage does not. Movement time is also slowed due to a disruption of both the aiming and ballistic processes controlling movement.

1. Introduction

Moderate to severe hypoxia degrades performance on virtually any complex perceptual–motor task (Tune 1964). One approach to understanding the causes of this degradation is to isolate the reaction time and movement time components of a task and then determine how hypoxia influences the structural, functional and strategic mechanisms underlying these components (Hockey and Hamilton 1983, Sanders 1983, Fowler *et al.* 1985).

Ledwith (1970) and Fowler *et al.* (1982 a) have investigated the effects of hypoxia on tasks involving both reaction time and movement time. In the latter study, an SCRT (serial choice response time) task was used which consisted of a set of push-button and LED (light-emitting diode) pairs arrayed in the horizontal plane. The LEDs were illuminated randomly and the subject extinguished each one by striking the appropriate push-button with a rubber-tipped wand. Stimulus brightness, the number of choices and movement distance were varied factorially. It was found that hypoxia increased the response time more under low than under high brightness, added a

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constant to the function for the number of choices and increased the slope of the function for movement distance. Fowler *et al.* (1982 a) proposed that hypoxia influenced the SCRT in two distinct ways. One was by increasing the intercept of the slope of the function derived from the Hick–Hyman Law (Hick 1952, Hyman 1953) and the other was by increasing the slope of the function derived from Fitts' Law (Fitts 1954). However, this proposal was tentative because a small but significant interaction was observed between the number of choices and movement distance, thereby calling into question the accuracy of the parameter estimates for each law.

Blocking is defined as the momentary interruption of processing interspersed with normal performance so that a bimodal distribution of responses is created (Broadbent 1958). Although a number of authors have claimed that blocking occurs with hypoxia (Bills 1937, Maag 1957, Gill *et al.* 1964), Fowler *et al.* (1982 a) concluded that the presence of blocking alone was doubtful in their experiment. It was clear that hypoxia slowed all responses but some extra-long responses were observed and the possiblity of blocking in combination with general slowing could not be ruled out. It was suggested, however, that these extra-long responses were more likely due to incorrect anticipatory movements.

The research discussed above raises the possibility that the slowing of SCRT performance under hypoxia can in large measure be accounted for by an additive effect on the Hick–Hyman Law, an interactive effect on Fitts' Law and by a generalized slowing of response time. The purpose of the present two experiments was to investigate this by using two relatively simple tasks; one representing the reaction time component (experiment 1) and the other the movement time component (experiment 2) of the SCRT task, so that the effects of hypoxia on each law could be measured with precision. Any interpretation of blocking on the SCRT task was confounded by incorrect anticipatory responses which reflect variations in strategy on the part of the subjects. To control for this kind of strategic variable in the present experiments, accuracy was strictly controlled so that a setting on the speed–accuracy operating characteristic was maintained within close limits.

In experiment 1, the effects of hypoxia on the Hick–Hyman Law were investigated with a modified version of the SCRT task which eliminated movement time and allowed the measurement of choice reaction time rather than choice response time. The possibility that hypoxia causes blocking in conjunction with general slowing was investigated in this experiment by examining the frequency distributions of reaction times which were uncontaminated by the possible presence of incorrect anticipatory movements. In experiment 2, the effects of hypoxia on Fitts' Law were investigated with a reciprocal tapping task in which movement amplitude and target width were varied to produce a range of IDs (Indices of Difficulty). In addition, the effects of hypoxia on the movement processes of visual aiming and ballistic control were assessed by regressing movement time on target width with movement amplitude kept constant, and movement time on movement amplitude with target width kept constant, respectively (Welford *et al.* 1969, Hay 1981, Fowler *et al.* 1982 b).

2. Method

2.1. *Subjects*

Fourteen paid student volunteers from York University, aged 20–27 years, were used as subjects. They were medically screened and each signed an informed consent document. Six (three males, three females) participated in experiment 1 and eight (seven females, one male) in experiment 2.

2.2. *Apparatus*

Choice reaction time was measured with a modified version of the SCRT task. Five, four or three finger-operated push-buttons (Microswitch model PK85022) were mounted in the horizontal plane of a rectangular module with a red light-emitting diode (LED, Fairchild model FLV560) adjacent to each button. The buttons were individually adjustable to accommodate different hand sizes and finger combinations. The LEDs were randomly lit in succession by a PDP 11/04 computer as the subject extinguished each one by depressing the adjacent button. The computer recorded reaction time and the number of errors (pressing an unlit button).

Movement time was measured with a reciprocal tapping task which has been described in detail elsewhere (Fowler *et al.* 1982 b). Briefly, pairs of targets, each consisting of two parallel lines 4 cm long, were printed on sheets of paper. Seven combinations of W (distance between the two parallel lines comprising a target) and A (distance between the centres of the two targets) were used. The combinations consisted of $W = 2{\cdot}4$, $1{\cdot}2$, $0{\cdot}8$ and $0{\cdot}6$ cm with $A = 21$ cm; and $A = 28$, 21, 14 and 7 cm with $W = 0{\cdot}6$ cm. The subject used a sharpened pencil for tapping in order to create a permanent record of the point of impact of each movement.

The method of inducing hypoxia has been described in detail elsewhere (Fowler *et al.* 1985). Briefly, a low-oxygen mixture was breathed via an oro-nasal mask (Canadian Forces model A13A) while SaO_2 (arterial oxyhaemoglobin saturation) was monitored with an ear oximeter (Hewlett Packard model 47201A) and recorded on a strip chart recorder (Perkin Elmer model 023). The desired level of SaO_2 could be maintained by switching between O_2 mixtures ranging from 8% to 13% O_2 balanced with N_2, which were contained in high-pressure bottles.

2.3. *Design*

Both experiments used a repeated measures design with three parts; a pre-hypoxia air breathing control, a hypoxia condition and a post-hypoxia air breathing control. In experiment 1, there were three levels of choice (2, 3 and 4) which were presented randomly in each part. In experiment 2, the seven combinations of A and W were randomly presented twice in each part.

2.4. *Procedure*

Prior to each experiment, the subjects practised the task. By breathing both air and a hypoxic gas mixture in a number of sessions until their performance was stable, they could maintain a specified error rate and they could inhibit hyperventilation. Performance stability was established by plotting the data for each subject from each practice session until the initial sharp improvements in performance were no longer evident. In experiment 1, the subjects were tested individually in a single session while seated with their fingers resting comfortably on the SCRT buttons. The index and middle fingers of the preferred hand and the index finger of the non-preferred hand were used in the two-choice condition. The index and middle fingers of both hands were used in the three-choice condition and the thumb of the preferred hand was added in the four-choice condition. The task was to continuously extinguish the lighted LED as quickly as possible over a period of 90 s while maintaining an error rate of $5 \pm 1\%$. If the error criterion was exceeded, the data were discarded and the run repeated immediately. This happened rarely. After the pre-hypoxia controls were collected, SaO_2 was lowered over a period of 10–20 min and stabilized at $67 \pm 2\%$. The post-

hypoxia controls were collected after SaO_2 had returned to normal values (95–96%). The total time for the session was approximately 60 min.

The procedure in experiment 2 was identical to that in experiment 1, except that the task was to tap back and forth between the targets as quickly as possible while maintaining an error rate of exactly 10% (an error consisted of a tap falling outside the parallel lines constituting a target). Data were gathered in sets of 50 taps, a tap consisting of a movement from one target to the other. Each set commenced with the pencil centred on the left target and, on command, the subject tapped back and forth while the experimenter timed 50 taps with a stop-watch. If the error rate was not 10%, the data were discarded and the run repeated immediately. Repeat runs were not as rare as in experiment 1 but were still uncommon. The total time for the session was approximately 90 min.

3. Results

SaO_2 was calculated for each subject by averaging the readings from the pen recorder at 10 s intervals. Averaged across subjects, the values were $67{\cdot}0 \pm 0{\cdot}4\%$ (standard error of mean, s.e.m.) for experiment 1 and $67{\cdot}5 \pm 0{\cdot}1\%$ for experiment 2. These hypoxic levels are equivalent to a calculated altitude of approximately 4700 m (Fowler *et al.* 1985).

In experiment 1, the median latency for the first correct responses (i.e. omitting responses to an unlit LED and the subsequent error-correcting response) was calculated for every subject in each condition. To determine whether or not the pre- and post-hypoxia controls differed from one another, a 6 subjects $\times$ 3 levels of choice $\times$ 2 controls repeated measures analysis of variance was performed on these data. Levels of choice ($F[2,10] = 37{\cdot}65$; $p < 0{\cdot}001$) was the only significant effect. Consequently, the controls were pooled for comparison with the hypoxia condition. The averaged data, fitted with linear functions by the method of least squares, are illustrated in figure 1. Statistical analysis on the individual slopes and intercepts confirmed what is evident in figure 1. Hypoxia increased the intercept ($t(5) = 4{\cdot}65$; $p < 0{\cdot}01$) but not the slope ($t(5) < 1$) of the Hick–Hyman function.

Blocking was investigated by generating the frequency histograms of the first correct responses for every subject in each condition. There was no indication that the effects of hypoxia differed as a function of the number of choices. Therefore, the two-choice condition was chosen as representative, and these results are illustrated in figure 2. It can be seen that hypoxia shifted the distributions to the right. This is consistent with figure 1 and indicates slowing. On the other hand, there is no evidence of bimodality in the hypoxic distributions that would indicate blocking. In fact, apart from the shift to the right, the characters of the normoxic and hypoxic distributions are remarkably similar. In particular, it is evident that hypoxia did not influence the variability of the response pattern. This was confirmed by a correlated variance test ($t(4) = 1{\cdot}23$). Isolated extra-long responses are also of interest because they could be indicative of lapses of attention. Defining extra-long responses as those greater than three standard deviations from the mean, it was established that these did not differ between the normoxic and hypoxic conditions ($t(5) < 1$).

To determine how hypoxia influenced the pattern of responding around an error, the mean latency for each error, as well as the four latencies preceding and following it, were calculated. Once again, the effects of hypoxia did not vary with the number of choices; the four-choice condition, averaged across subjects, is illustrated in figure 3. It can be seen that hypoxia caused slowing but did not alter the pattern of responding around an error.

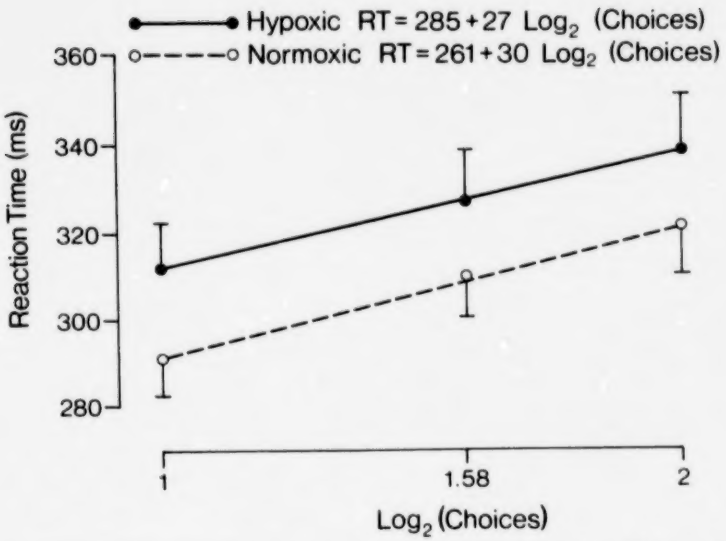

Figure 1. Mean reaction time as a function of $\log_2 n$, where n = the number of choices (Hyman 1953) in experiment 1. The bars represent s.e.m.s. Normoxic = pre-hypoxia condition.

In experiment 2, movement time was calculated by dividing the combined times of the two identical trials in each condition by 100. An 8 subjects × 7 target combinations × 2 pre- and post-controls repeated measures analysis of variance was performed to determine whether the pre- and post-hypoxia controls differed from one another. Target combinations ($F[6, 42] = 276{\cdot}51$; $p < 0{\cdot}001$) gave the only significant effect. Therefore, the controls were pooled for comparison with the hypoxia condition. These data, fitted with linear functions by the method of least squares, are illustrated in figure 4. Although the fit of the data to the linear function is not ideal, it is evident that hypoxia increased the slope of Fitts' Law ($t(7) = 6{\cdot}18$; $p < 0{\cdot}001$). An alternative approach to analysing the same data is illustrated in figure 5. In figure 5A, movement time is regressed on target width with movement amplitude held constant. In figure 5B, movement time is regressed on movement amplitude with target width held constant. Hypoxia increased the slope of both functions ($t(7) = 4{\cdot}32$; $p < 0{\cdot}01$ and $t(7) = 2{\cdot}40$; $p < 0{\cdot}05$), respectively. It should also be noted that these separate analyses appear to provide a better fit to the data than the composite analysis in figure 4.

4. Discussion

Using two simpler tasks, the results of these experiments parallel those found previously with the more complex SCRT task (Fowler *et al.* 1982a). Hypoxia influenced the number of choices additively and movement difficulty interactively. This establishes a link between the effects of hypoxia on the SCRT task and on the laws governing performance on the task.

The additive slowing of reaction time was demonstrated in experiment 1 by the increase in the intercept of the Hick–Hyman function (figure 1). One way to interpret this result is to assume a structural deficit and apply additive factors logic (Sanders 1983). On this basis, it appears that some stage other than that of stimulus–response choice was slowed since the intercept increased but not the slope. One possibility is that hypoxia decreased the apparent brightness of the stimuli, thereby slowing reaction

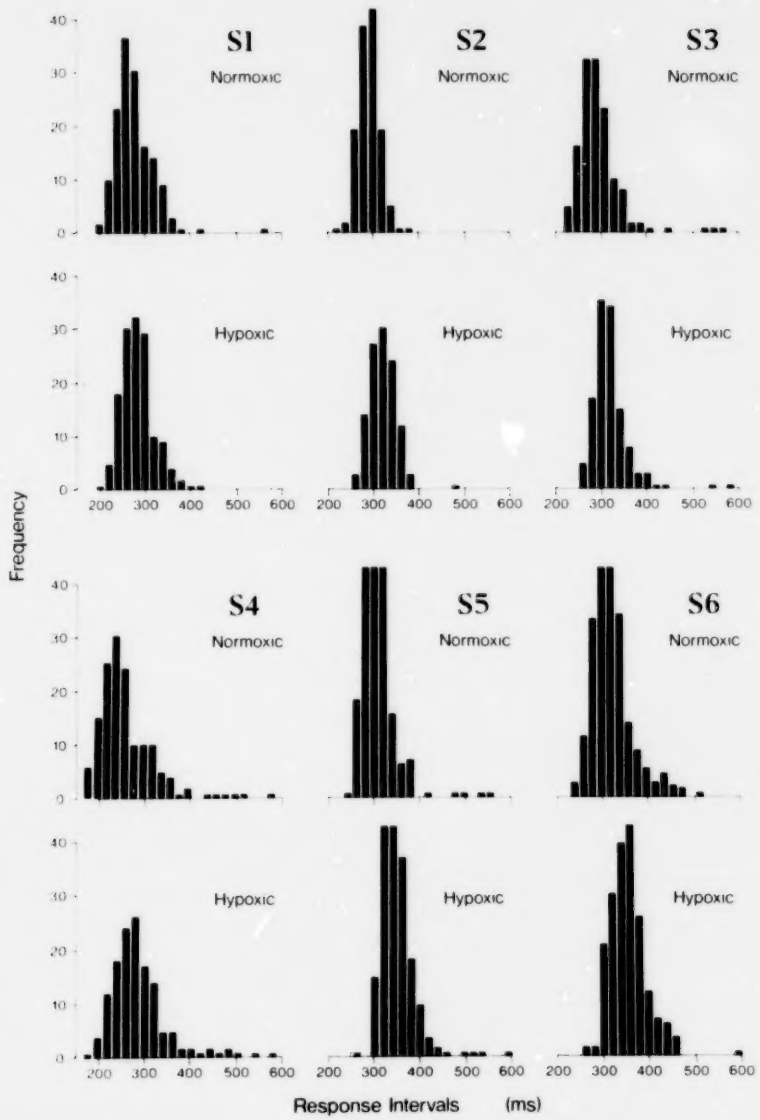

Figure 2. Frequency histograms of reaction time for each subject (S) in the two-choice condition in experiment 1. Normoxic = pre-hypoxia condition.

time (Teichner 1954). This explanation is consistent with the sensitivity of brightness discrimination to hypoxia (Hecht *et al.* 1946) and the fact that hypoxia slows response time more with low than with high brightness stimuli (Fowler *et al.* 1982 a, Fowler *et al.* 1987). Of course, this does not preclude the possibility that other stages of processing may also be slowed.

Another finding in experiment 1 was the absence of bimodality, or even any

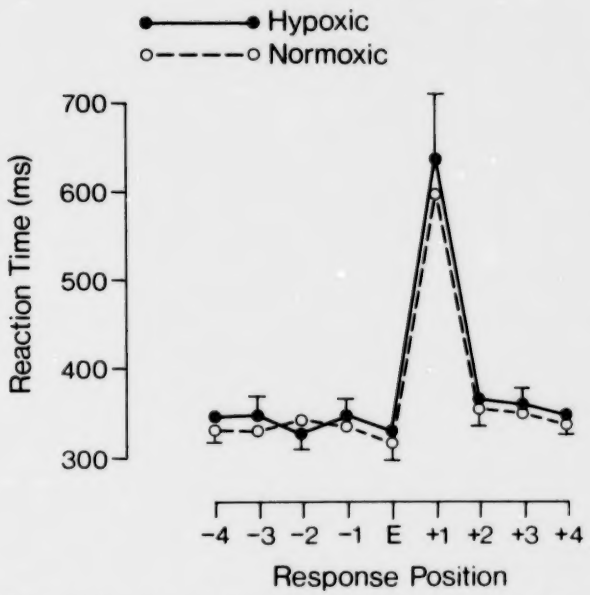

Figure 3. Mean reaction time as a function of response position relative to an error (E) in experiment 1. The bars represent s.e.m.s.

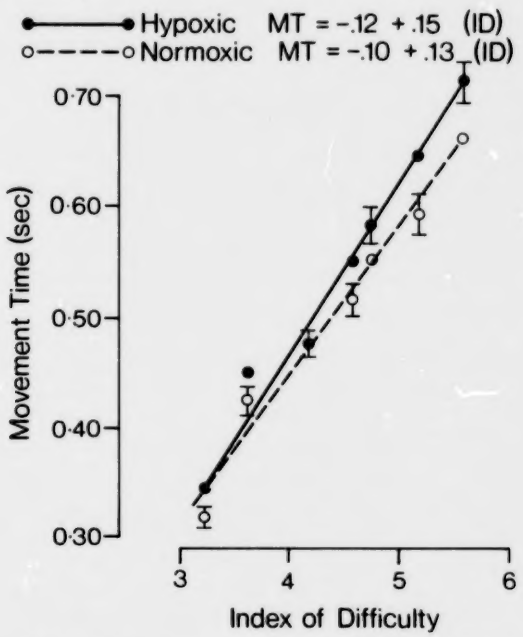

Figure 4. Mean movement time as a function of ID (Index of Difficulty) in experiment 2. $ID = \log_2 A/W + 0{\cdot}5$, where A = amplitude of movement and W = target width (Welford *et al.* 1969). The bars represent s.e.m.s.

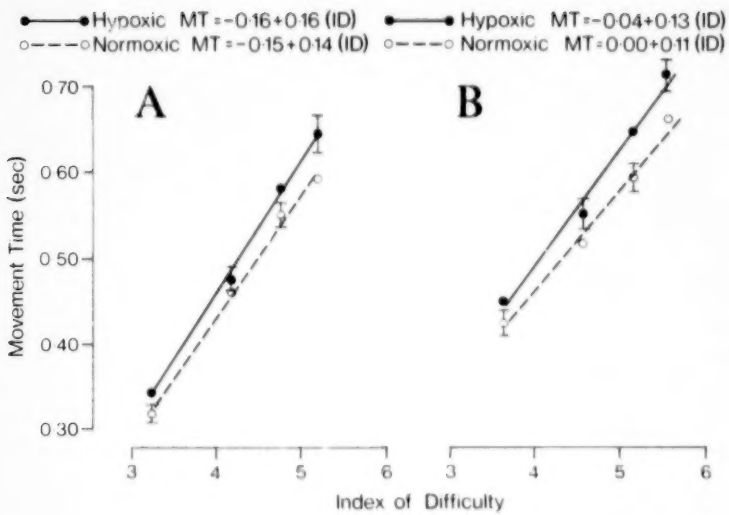

Figure 5. Mean movement time as a function of ID (Index of Difficulty) in experiment 2. (A) Movement time regressed on target width with amplitude constant. (B) Movement time regressed on amplitude with width constant. The bars represent s.e.m.s.

additional extra-long responses, in the frequency distributions under hypoxia. Rather, hypoxia caused a general slowing of response time (figure 2). This experiment therefore provides no support for any version of the central blocking hypothesis, and it seems likely that the extra-long responses observed by Fowler *et al.* (1982 a) were due to incorrect anticipatory movements, as these authors suggested. However, the present results do not entirely rule out the possibility of peripheral blocking at the muscular level, which influences only movement time. The pattern of responding around an error observed in experiment 1 has been reported with other serial tasks, including typing (Fisher 1975, Rabbitt 1981, Salthouse 1986). Hypoxia slowed but did not alter this pattern (figure 3). This is in agreement with the previous study by Fowler *et al.* (1982 a), who suggested that this slowing could be due to the need to process additional information in the form of error recognition and correction. The present results are consistent with this explanation since reaction time, rather than movement time, was measured, and imply that this aspect of cognitive processing is unaffected by hypoxia.

The interactive slowing of movement time by hypoxia was revealed in experiment 2 by an increase in the slope of the function representing Fitts' Law (figure 4). When the regression technique of Welford *et al.* (1969) was applied to these data, both slopes were increased by hypoxia (figure 5). These results suggest that hypoxia disrupts the aiming and ballistic processes governing movement. The locus of these effects is a matter for speculation at present but, in the case of the ballistic process, a loss of efficiency is consistent with the tremors, twitches and involuntary movements that have been observed with hypoxia (Van Liere and Stickney 1963). Two other points should be noted about the movement time data. First, the slopes representing the aiming and ballistic processes do not necessarily shift together, as was the case in the present experiment. Differential changes have been observed as a function of age (Hay 1981) and inert gas narcosis (Fowler *et al.* 1982 b). Second, the better fit of the data in figure 5,

compared to that in figure 4, is consistent with previous results indicating that Fitts' Law cannot be fully explained by a unitary process (Sheridan 1979, 1984).

In both experiments, accuracy was strictly controlled so that slowing due to structural or functional variables would not be confounded with strategic shifts in the speed–accuracy trade-off setting. The fact that it was possible to control accuracy in this fashion is significant because it usually deteriorates under hypoxia (Tichauer 1963, Van Liere and Stickney 1963, Fowler *et al.* 1982 a). Consequently, the present results support the argument that decreases in accuracy under hypoxia arise from trading accuracy for speed (Cahoon 1972). In experiment 1, it was also found that the character of the frequency distributions under normoxic and hypoxic conditions did not differ markedly (figure 2). In particular, it was observed that the variability of responding did not differ nor was there any sign of extra-long responses which might indicate inattention. These results demonstrate that another strategic aspect of performance, the moment-to-moment control of responding (Rabbitt 1981), is not necessarily disrupted under hypoxia. Early in training, prior to the commencement of the experiment, increases in the variability of the frequency distributions under hypoxia were evident. It therefore seems reasonable to suppose that, in order to meet the strict overall accuracy requirements for this experiment, the subjects were forced to pay close attention to moment-to-moment performance. In general, these results suggest that changes in strategic variables are not a necessary part of hypoxic performance decrements and that they can be brought under control or manipulated with instruction and training.

In summary, a tripartite model of information processing, involving structural, functional and strategic variables, appears to be a useful approach to analysing the effects of hypoxia on performance (Sanders 1983, Fowler *et al.* 1985). At present, the evidence indicates that specific structural processes are implicated in slowing. A second and more subtle source of change, which may interact with slowing, arises from alterations in the strategies used to perform a task (Cahoon 1972). This suggests that a model which seeks to explain the effects of hypoxia on performance should incorporate a description of structural and/or functional deficits as well as the strategic changes which play a role in determining how these deficits are expressed as patterns of behaviour on particular tasks (Hockey and Hamilton 1983).

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Il a déjà été démontré qu'une hypoxie perturbe les performances d'une tâches de choix sériels (SCRT). Deux expériences ont été effectuées pour étudier plus complètement la nature de cette perturbation. L'hypoxie a été induite par des mélanges appauvris en oxygène et une saturation en oxyhémoglobine artérielle (SaO_2) maintenue à un niveau équivalent à une altitude d'environ 4700 m. Dans la première expérience, le temps de réaction de choix a été déterminé sur une version de la SCRT qui éliminait le temps de mouvement. L'hypoxie augmentait l'ordonnée à l'origine, mais non la pente de la fonction de Hick–Hyman. Dans la deuxième expérience, le

temps de mouvement a été mesuré au moyen d'une tâche de tapping réciproque. L'hypoxie n'augmentait non seulement la pente de la fonction de Fitts, mais également les pentes déterminées lorsqu'on analyse séparément la largeur de la cible et l'amplitude du mouvement. Dans les deux expériences, le taux des erreurs a été maintenu constant. Ces résultats montrent que l'hypoxie perturbe les composantes de temps de réaction et de temps de mouvement dans les performances à une tâche de SCRT. On admet que le temps de réaction est allongé, mais non 'bloque' et cet allongement est dû à une diminution de la sensibilité à la brillance, alors que le processus de choix n'est pas affecté. Le temps de mouvement est également allongé à cause de la perturbation des processus ballistiques et de visée qui contrôlent le mouvement.

Schon früher wurde gezeigt, daß Hypoxie die Leistung bei einer visuellen, seriellen Wahlreaktionszeit-Aufgabe (SCRT) stört. Zur eingehenderen Erkundung der Natur dieser Störung wurden zwei Experimente durchgeführt. Die Hypoxie wurde mit sauerstoffarmen Gemischen und SaO_2 bei einem Pegel entsprechend einer Höhe von ungefähr 4700 m gehalten. Im Experiment 1 wurde die Wahlreaktionszeit bei einer Version der SCRT-Aufgabe gemessen, die die Bewegungszeit eliminiert. Die Hypoxie vergrößerte die Unterbrechung (intercept) nicht aber die Steigung (slope) der Hick–Hyman-Funktion. Im Experiment 2 wurde die Bewegungszeit bei einer reziproken Tapping-Aufgabe gemessen. Die Hypoxie vergrößerte nicht nur die Steigung der Fitt's-Funktion, sondern auch die Steigungen, die bei separater Analyse von Zielentfernung und Bewegungsamplitude entstanden. In beiden Experimenten wurde die Fehlerrate konstant gehalten. Die Ergebnisse zeigen, daß Hypoxie die Reaktionszeit und Bewegungszeit-Komponenten bei SCRT-Aufgaben stört. Es wird angenommen, daß die Reaktion eher verlangsamt als blockiert wird und daß verminderte Helligkeitsempfindlichkeit zu diewer Verlangsamung beiträgt, jedoch nicht die Wahlentscheidungsperiode. Die Bewegungszeit eird ebenfalls verlangsamt entsprechend einer Störung sowohl der ballistischen als auch der Zielbewegung.

低酸素症が視覚SCRT（系列選択反応時間）作業の成績を低下させることが以前示された。2つの実験を実施してこの成績阻害をさらに調査した。低酸素症は低酸素混合物で誘発し，SaO_2（動脈オキシヘモグロビン飽和）は約4,700 mの高度に相当するレベルに維持された。実験1では，動作時間を除外したSCRT作業で選択反応時間を測定した。低酸素症はヒック－ハイマン関数の傾斜でなく，切片を増大させる。実験2では，動作時間は逆比例タッフ作業で測定した。低酸素症はフィッ関数の傾斜だけでなく，目標幅と動作振幅を別々に分析したときに生じた傾斜も増大させた。両方の実験で，誤り率は一定に維持された。これらの結果は低酸素症がSCRT成績の反応時間と動作時間の成分を阻害することを示す。反応時間が「阻止」されるのではなく減少し，低下した明るさ感度がこの反応時間短縮に貢献し，選択処理段階が貢献しないと考えられる。動作時間は動作を制御する照準と弾道の過程の両方の阻害によっても減少する。